LOAD FLOW STUDIES WITH UPFC POWER INJECTION MODEL

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF

Master of Technology
in
Power Control and Drives

By

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Department of Electrical Engineering
National Institute of Technology
Rourkela
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Under the Guidance of

Prof. S.Ganguly

Department of Electrical Engineering
National Institute of Technology
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2013

Dedicated

to

my beloved parents & teachers

Department of Electrical Engineering
National Institute of Technology, Rourkela

CERTIFICATE

*This is to certify that the thesis entitled " **Load Flow Studies with UPFC Power Injection Model** " by Mr. Mithu Sarkar, submitted to the National Institute of Technology, Rourkela (Deemed University) for the award of Master of Technology by Research in Electrical Engineering, is a record of bona fide research work carried out by him in the Department of Electrical Engineering, under my supervision. I believe that this thesis fulfills part of the requirements for the award of degree of Master of Technology by Research. The results embodied in the thesis have not been submitted for the award of any other degree elsewhere.*

Place: Rourkela

Prof. S.Ganguly

Date:

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Mithu Sarkar

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ABBREVIATIONS

$*$	Complex conjugate
V_i	Voltage magnitude of bus i
V_j	Voltage magnitude of bus j
$\bar{V}_i^{/}$	Imaginary voltage behind the series reactance
θ_i	Phase angle of voltage of bus i
θ_j	Phase angle of voltage of bus
θ_{ij}	Difference of phase angle of bus 'i' and 'j'
$\Delta\theta$	Vector of incremental change in phase angle of nodal voltages
V_{se}	The output voltage of series branch of UPFC
V_{sh}	The output voltage of shunt branch of UPFC
ΔV	Vector of incremental change in magnitude of nodal voltages
I_{se}	Current source in parallel with transmission line
I_{ij}	Current flowing from bus i to bus j
r	Per unit value of output voltage of series branch of UPFC
γ	Phase angle difference between Vi and Vse
X_{se}	Leakage reactance of series coupling transformer of UPFC
b_{se}	Susceptance of series coupling transformer
G	Network conductance
B	Network susceptance
S_{is}	Equivalent complex power injected into bus i by the series branch of UPFC
S_{js}	Equivalent complex power injected into bus j by the series branch of UPFC
P_{is}	Equivalent real power injected into bus i by the series branch of UPFC
P_{js}	Equivalent real power injected into bus j by the series branch of UPFC
Q_{is}	Equivalent reactive power injected into bus i by the series branch of UPFC
Q_{js}	Equivalent reactive power injected into bus j by the series branch of UPFC
P_{cov1}	Real power delivered absorbed by the shunt branch of UPFC
P_{cov2}	Injected real power by the series branch of UPFC
S_{cov1}	Injected complex power by the series branch of UPFC
Q_{cov1}	Reactive power delivered or absorbed by the shunt branch of UPFC
Q_{cov2}	Injected reactive power by the series branch of UPFC

$P_{i,upfc}$	Equivalent total real power injected into bus i by UPFC
$P_{j,upfc}$	Equivalent total real power injected into bus j by UPFC
$Q_{i,upfc}$	Equivalent total reactive power injected into bus i by UPFC
$P_{i,upfc}$	Equivalent total reactive power injected into bus j by UPFC
ΔP	Real power mismatch vector

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Abstract

Now-a-days the Flexible AC Transmission Systems (FACTS) is very popular and essential device in power systems. After introducing the FACTS technology, power flow along the transmission lines becomes more flexible and controllable. Several FACTS-devices have been introduced for various applications in power system. Among a variety of FACTS controllers, Unified Power Flow Controller (UPFC) is the most powerful and versatile device. The UPFC is a device which can control the flow of real and reactive power by injection of a voltage in series with the transmission line. Both the magnitude and the phase angle of the voltage can be varied independently. This thesis is focused on to improve the bus voltage and to reduce the active and reactive power losses in the transmission lines incorporating steady state model of UPFC in Newton-Raphson (NR) power flow algorithm. The steady state model of the UPFC, derived from two voltage source representation, is presented and analyzed in detail. A MATLAB program is executed to incorporate the UPFC model in NR Load flow algorithm. To determine the steady state performance of the UPFC in the load flow studies a IEEE 30 and IEEE-14, IEEE-5 bus systems has taken.

Chapter 1

INTRODUCTION

1.1 Introduction

Power Generation and Transmission is a complex process, wherever power is to be transferred, the two main components are active and reactive power. In a three phase ac power system active and reactive power flows from the generating station to the load through different transmission lines and networks buses. The active and reactive power flow in transmission line is called power flow or load flow. Power flow studies provide a systematic mathematical approach for determination of various bus voltages, there phase angle, active and reactive power flows through different lines, generators and loads at steady state condition. Power flow analysis is also used to determine the steady state operating condition of a power system. For the planning and operation of power distribution system, Power flow analysis is used. It is very important to control the power flow along the transmission line. Thus to control and improve the performance of ac power systems, we need the various different types compensators.

The continuing rapid development of high-power semiconductor technology now makes it possible to control electrical power systems by means of power electronic devices [1,2]. These devices constitute an emerging technology called FACTS (flexible alternating current transmission systems) [2, 3]. The FACTS technology opens up new opportunities for controlling the both types of powers and enhancing the usable capacity of present transmission systems. The possibility that power through a line can be controlled enables a large potential of increasing the capacity of lines. This opportunity is arises through the ability of FACTS controllers to adjust the power system electrical parameters including series and shunt impedances, current, voltage, phase angle, and the damping oscillations etc. The implementation of such equipments requires the different power electronics-based compensators and controllers [5].The FACTS devices use various power electronics devices such as Thyristors , Gate turn offs(GTO), Insulated gate bipolar transistors(IGBT), Insulated Gate Commutated thyristors (IGCT),they can be controlled very fast as well as different control algorithms adapted to various situations. FACTS technology has a lots of benefits, such as greater power flow control ability, increased the loading of existing transmission circuits, damping of power system oscillations, has less bed impact on environmental and , has the less cost than other alternative techniques of transmission system is used.

The UPFC is one of the most versatile device. It cannot only perform the functions of the static synchronous compensator (STATCOM), thyristor switched capacitor (TSC) thyristor controlled reactor (TCR), and the phase angle regulator but also provides additional flexibility by combining some of the functions of the above controllers [1]. The main function of the UPFC is to control the flow of real and reactive power by injection of a voltage in series with the transmission line. Both the magnitude as well as the phase angle of the voltage can be varied independently. Real and reactive power flow control can allow for power flow in prescribed routes, transmission lines loading is closer to their thermal limits and can be utilized for improving transient and small signal stability of the power system.

1.2 Literature Review:

The demand of electric power is increasing day by day. This situation has necessitated a review of the traditional power system concepts and practices to achieve greater operating flexibility and better utilization of existing power systems. During the last two decades, various high-power semiconductor device and control technologies have been introduced [1, 4]. The various thyristor circuits used in to generate and control the reactive power [4, 5, 6, 7].These technologies have been instrumental in the broad application of high voltage DC and AC transmissions. They have already made a significant impact on AC transmission via the increasing use of thyristor controlled static VAR compensators (SVCs).The UPFC is the one of most powerful Facts device, introduced by Gyugyi, L[8,9,10].Various mathematical model of UPFC has been introduced depend upon various purpose of application. For the Power system stability studies the UPFC current injection model is used, which improve the dynamic performance of the system [11]. In this model the shunt compensation of UPFC is controlled to maintain the system bus voltage and the two components of UPFC series voltage, which are in phase voltage and quadrature voltage, are coordinated to respond to the power variations of the line. In case of static performance the power injection model is used. This is particularly the case in the area of power flow analysis where, two very constrained models have been published [12, and 13,14]. Reference [12] presents an elegant approach. The sending and receiving ends of the UPFC are decoupled. The active and reactive power loads in the PQ bus and the voltage magnitude at the PV bus are set at the values to be controlled by the UPFC. The active power injected into the PV bus has the same value as the active power extracted in the PQ bus since the UPFC and coupling transformers are assumed to be lossless. Reference [13] takes the approach of modeling the UPFC as a series reactance together with a set of active and reactive nodal power injections at each end of the series reactance. These powers are expressed as function of terminal, nodal voltages, and the output voltage of the series source which represents the UPFC series converter. The UPFC injection model has implemented into a full Newton-Raphson program by adding the UPFC power injections model and by derivatives the elements of jacobian matrix with respect to the AC network state variables, i.e. nodal voltage magnitude and angles, at the appropriate locations in the mismatch vector and Jacobian matrix. The mismatch vectors original dimension and Jacobian matrix are not altered at all. The UPFC stability to regulating power flow through a transmission line and to minimize power losses, without generation re-scheduling, is shown by numeric examples. The attraction of this formulation is that it can be implemented very easily in existing power flow programs. Another model of UPFC in terms of power flow control is presented in [14].In that model state variables of UPFC are incorporated inside the Jacobian matrix and mismatch equations, leading to vary the iterative solutions. UPFC controls the active and reactive power simultaneously and the voltage magnitude also. At initial conditions a set of analytical equations has been derived to provide UPFC. The losses of the UPFC coupling transformers have taken into account. UPFC have the capability to regulate the power flow and minimizing the power losses simultaneously [15]. M Tomay and A.M. Vuralin the power injection model of (UPFC) the operational losses also taken into account and the effects of UPFC location on different power system parameters are entirely investigated [16]. A general sequential power flow algorithm based on an injection model of FACTS devices has been presented in [17]. The algorithm is compatible with Newton-Raphson and decoupled algorithms. It is important to ascertain the location for placement of UPFC which is suitable for various contingencies. An effective placement strategy for UPFC is proposed [18]. The method uses Line Stability index which is sensitive to line flow to screen down the possible locations for UPFC.

1.3 Motivation:

Day by day all over the world the demand of electric power is increasing. Not only that, the demand of power by the consumer is more than the power flowing through the transmission line. In order to provide the power that achieved the consumers demand the FACTS technology introduced. The maximum loads which are used in daily life or industrial purpose are inductive type. This type of load are consumed the reactive power. To control and regulate the active and reactive power the various FACTS device are used. The UPFC is most promising device among the entire FACTS device. The UPFC can control transmission voltage, impedance, and phase angle. The UPFC can also enhance the real and reactive power capacity of the system.

1.4 Thesis Objective:

The objectives of the research are:

1. To study the basic operation of UPFC
   - To study the model of UPFC and how it can's operated in the transmission system.
2. To incorporate UPFC in Newton Raphson's(NR) load flow algorithm.
3. To analyze the impact of UPFC in the transmission line.
   - To reduce the transmission power losses by incorporating UPFC, three different cases will be tested

1.5FACTS Controller

Flexible AC Transmission System (FACTS): Alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability.

The various basic applications of FACTS-devices are:

- power flow control
- increase of transmission capability
- voltage control
- reactive power compensation, stability improvement
- Power quality improvement
- Power conditioning.

The fig 1.1 is for classification of FACTS Controllers Based on power electronic devices. In this fig, left hand side column of FACTS-devices employs the use of thyristor valves or converters. This valves or converters are well known since several years. They have low switching frequency and low losses.

The devices of the right hand side column of the fig has more advanced technology of voltage source converters based mainly on Insulated Gate Bipolar Transistors (IGBT) or Insulated Gate Commutated Thyristors (IGCT). Pulse width modulation technique is used to control the magnitude and phase of the voltage. They have high modulation frequency.

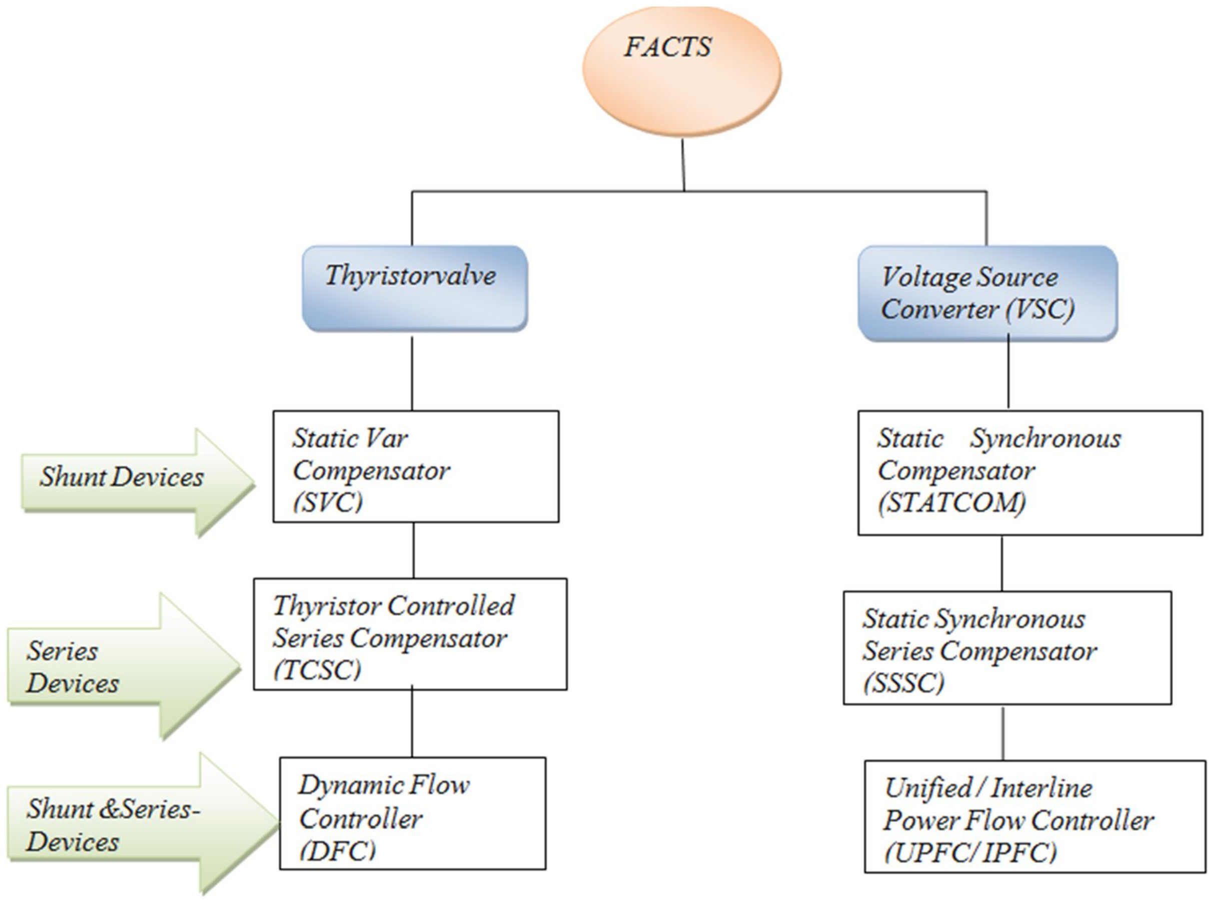


Fig1.1 Overview Of major FACTS devices in terms of on power electronic devices

1.5.1Thyristor Based FACTS Devices:

1.5.1. 1 SVC

A shunt- connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage).This is a general term for a Thyristor Controlled Reactor (TCR) or Thyristor Switched Reactor (TSR) and/or Thyristor Switched Capacitor (TSC). The term, "SVC" has been used for shunt connected compensators, which are based on thyristors without gate turn-off capability. It includes separate equipment for leading and lagging vars ; the thyristor –controlled or thyristor – switched reactor for absorbing reactive power and thyristor – switched capacitor for supplying the reactive power[2],[4].

1.5.1.2 Thyristor Controlled Series Compensator (TCSC):

It is designed based on the thyristor based FACTS technology that has the ability to control the line impedance with a thyristor-controlled capacitor placed in series with the transmission line. It is used to increase the transmission line capability by installing a series capacitor that reduces the net series impedance thus allowing additional power to be transferred. TCSC device consists of three main components: Capacitor bank, bypass inductor and two bidirectional thyristors.

1.5.2Voltage Source Converter Based FACTS Devices:

1.5.2. 1 Static Synchronous Series Compensator (SSSC):

Static Synchronous Series Compensator is based on solid-state voltage source converter designed to generate the desired voltage magnitude independent of line current. SSSC consists of a converter, DC bus (storage unit) and coupling transformer. The dc bus uses the inverter to synthesize an ac voltage waveform that is inserted in series with transmission line through the transformer with an appropriate phase angle and line current. If the injected voltage is in phase with the line current it exchanges a real power and if the injected voltage is in quadrature with line current it exchanges a reactive power. Therefore, it has the ability to exchange both the real and reactive power in a transmission line [19].

1.5.2.2 Static Synchronous Compensator (STATCOM):

It is designed based on Voltage source converter (VSC) electronic device with Gate turn off thyristor and dc capacitor coupled with a step down transformer tied to a transmission line. It converts the dc input voltage into ac output voltages to compensate the active and reactive power of the system. The STATCOM has better characteristics than SVC and it is used for voltage control and reactive power compensation. STATCOM placed on a transmission network improve the voltage stability of a power system by controlling the voltage in transmission and distribution systems, improves the damping power oscillation in transmission system, and provides the desired reactive power compensation of a power system

1.5.2.3 Unified Power Flow Controller (UPFC):

It is designed by combining the series compensator (SSSC) and shunt compensator (STATCOM) coupled with a common DC capacitor. It provides the ability to simultaneously control all the transmission parameters of power systems, i.e. voltage, impedance and phase angle. it consists of two converters – one connected in series with the transmission line through a series inserted transformer and the other one connected in shunt with the transmission line through a shunt transformer. The DC terminal of the two converters is connected together with a DC capacitor. The series converter control to inject voltage magnitude and phase angle in series with the line to control the active and reactive power flows on the transmission line. Hence the series converter will exchange active and reactive power with the line.

1.5.2.4 Interline Power Flow Controller (IPFC):

It is designed based on Convertible Static Compensator (CSC) of FACTS Controllers. IPFC consists of two series connected converters with two transmission lines. It is a device that provides a comprehensive power flow control for a multi-line transmission system and consists of multiple number of DC to AC converters, each providing series compensation for a different transmission line. The converters are linked together to their DC terminals and connected to the AC systems through their series coupling transformers. With this arrangement, it provides series reactive compensation in addition any converter can be controlled to supply active power to the common dc link from its own transmission line.

1.6 **Classification of Facts devices in terms of connection [2]:**

i) Series FACTS Controllers

ii) Shunt FACTS Controllers

iii) Combined Series-Series FACTS Controllers

iv) Combined Series-Shunt FACTS Controllers

1.6.1 Series FACTS Controllers:

These FACTS Controllers could be variable impedance such as capacitor, reactor or a power electronic based variable source. Typical series compensators use capacitors to reduce the equivalent reactance of a power line at rated frequency, thus increasing the voltage at the load terminals which in principle injects voltage in series with the line. As the voltage is in phase quadrature with the line current, the series Controllers only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well. The various important series compensator are Static Synchronous Series Compensator (SSSC),Thyristor-Controlled Series Compensation (TCSC).

- **Static Synchronous Series Compensator(SSSC):**
- **Thyristor-Controlled Series Compensation (TCSC).**

1.6.2 **Shunt FACTS Controllers**:

The shunt Controllers may be variable impedance such as

Capacitor, reactor or power electronic based variable source, which is shunt connected to the line in order to inject variable current. As long as the injected current is in phase quadrature with the line voltage, the shunt Controllers only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well. The important shunt compensators are StaticVar Compensator (SVC), Static Synchronous Compensator (STATCOM).

The objectives of a shunt compensator in a distribution system are as follows

- To compensate of poor load power factor so that the current drawn from the source Will have a nearly unity power factor.
- The Suppression of harmonics in loads so that the current drawn from source is nearly sinusoidal.
- To regulate the voltage for the loads that causes fluctuations in the supply voltage.

1.6.3 **Combined Series-Series FACTS Controllers**:

These Controllers are the combination of separate Series FACTS Controllers, which are controlled in a coordinated manner in a multiline transmission system. The configuration of Combined Series-Series FACTS Controller**s** provides independent series reactive power compensation for each line but also transfers real power among the lines via power link. The presence of power link between series controllers names this configuration as "Unified Series-Series Controller".

1.6.4 **Combined Series-Shunt FACTS Controllers**:

These are combination of separate shunt and series controller, which are controlled in a co-ordinate manner or a Unified Power Flow Controller with series and shunt elements. When the Shunt and Series FACTS Controllers are unified; there can be a real power exchange between the series and shunt controllers via power link.

Chapter 2

UNIFIED POWER FLOW CONTROLLER (UPFC)

2.1 A Review on UPFC

The UPFC is the most powerful and versatile FACTS-equipment used to control the power flow and stability of the power system. UPFC can be act static as well as dynamic condition also. Static is an analysis at the steady state condition and dynamic is an analysis at the transient condition such as faults occurs in transmission system. This chapter described about basic principle of UPFC and load flow analysis.

2.2 **Operation of UPFC**

The UPFC is a device which can control simultaneously all three parameters of line power flow (line impedance, voltage and phase angle) .It is a one of the FACTS family that used to optimum power flow in transmission. The UPFC is a combination of static synchronous compensator (STATCOM) and static synchronous compensator (SSSC).Both converters are operated from a common dc link with a dc storage capacitor. The real power can freely flow in either direction between the two-ac branches. Each converter can independently generate or absorb reactive power at the ac output terminals [6]. The controller provides the gating signals to the converter valves to provide the desired series voltages and simultaneously drawing the necessary shunt currents, In order to provide the required series injected voltage, the inverter requires a dc source with regenerative capabilities. The possible solution is to use the shunt inverter to support the dc bus voltage.

2.3 Advantages of UPFC

The UPFC can perform the function of STATCOM and SSSC and phase angle regulator. Besides that the UPFC also provides an additional flexibility by combining some of the function above. UPFC has also a unique capability to control real and reactive power flow simultaneously on a transmission system as well as to regulate the voltage at the bus where it’s connected.

The UPFC can also increase the capability of the power flow to the load demand until its reach its limit in the short period .At the same time the UPFC also can increase the security system by increases the limit of transient stability, fault and the over load demand .Lastly the UPFC also can reduce the value of the reactive power And will optimum the real power flow through the transmission line.

2.4 Theory of UPFC:

The Unified Power Flow Controller (UPFC) was proposed first time for real turn-off time control and dynamic compensation of ac transmission systems. The Unified Power Flow Controller is consists of two switching converters, which are considered as voltage sourced inverters using gate thyristor valves, as illustrated in Fig.2.1. These inverters, labeled "VSC1" and "VSC2" in the figure are operated with a common dc link provided by a dc storage capacitor. With this arrangement the ac power converter in which the real power can freely flow in either direction between the ac terminals of the two inverters and each inverter can independently generate as well as absorb the reactive power at its own ac output terminal .Since the series converter of the UPFC can inject a voltage with variable magnitude and phase angle it can exchange real power with the transmission line with the help of series transformer. However a UPFC as a whole (both converter) cannot supply or absorb real power in steady state (except for the power drawn to compensate for the losses).Unless it has a power source at DC terminals. Thus the shunt branch is required for compensate (from the system for any real power drawn/supplied by the series branch and the losses. when the power balance is not maintained, at that situation the capacitor cannot remain at a constant voltage. Shunt branch also can independently exchange reactive power with the system.

Inverter 2 provides the main function of the UPFC by injecting a voltage V_{pq} with controllable magnitude V_{pq} ($0 \leq V_{pq} \leq V_{pqmax}$) and phase angle ρ ($0 \leq \rho \leq 360°$), at the power frequency, insert with line via an insertion transformer. This injected voltage considered as synchronous ac voltage source .The transmission line current flows through this voltage source resulting in real and reactive power exchange between it and the ac system. Real power exchanged at the ac terminal (i.e., at the terminal of the insertion transformer) and the inverter help to convert the ac power into dc power, after that the dc power appears at the dc link as positive or negative real power demand. Reactive power exchanged at the ac terminal is generated internally by the inverter.

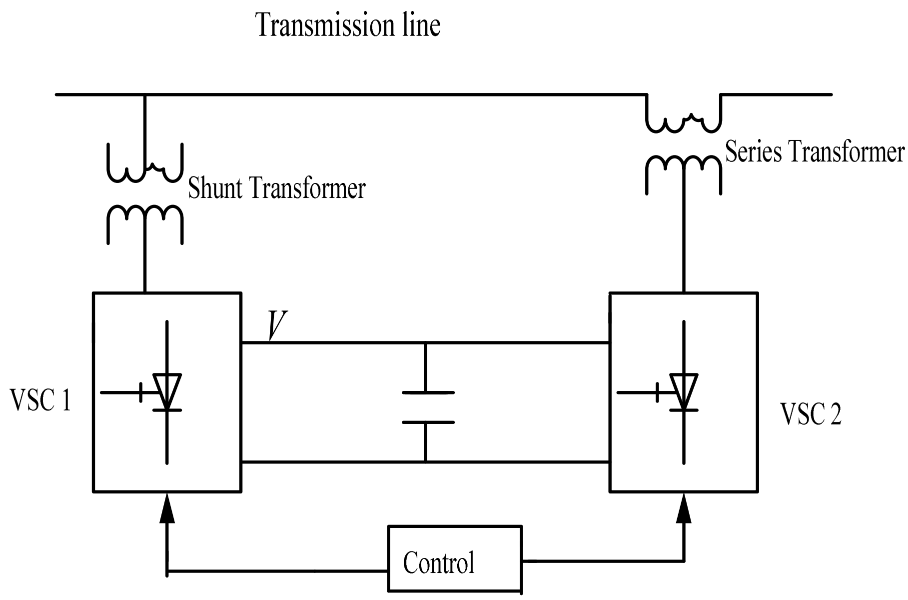


Fig: 2.1 The Schematic diagram of UPFC

The function of converter1 is to supply or absorb the real power demanded by converter 2 at the common dc link. The power of the dc link is converted back to ac and coupled to the transmission line via a shunt-connected transformer. If reactive power is required then inverter 1 can also generate or absorb controllable reactive power, so it can provide independent shunt reactive compensation for the line. It is also important to note that whereas there is a closed "direct" path for the real power negotiated by the action of series voltage injection through Inverters 1 and 2 back to the line, corresponding the reactive power exchanged is supplied or absorbed locally by Inverter 2 and therefore the reactive power does not flow through the line. So the Inverter 1 can be operated at a unity power factor or be controlled to have a reactive power exchange with the line independently of the reactive power exchanged by Inverter 2. That means there is no continuous reactive power flow through the UPFC.

The Unified Power Flow Controller from the stand point of conventional power transmission based on reactive series compensation, shunt compensation, and phase shifting, the UPFC is the only device which can fulfill all these functions and thereby meet multiple control objectives by adding the injected voltage V_{pq}, with appropriate amplitude and phase angle, to the terminal voltage V_0 Using phasor representation, the basic UPFC power flow control functions are illustrated in Fig.2.2.

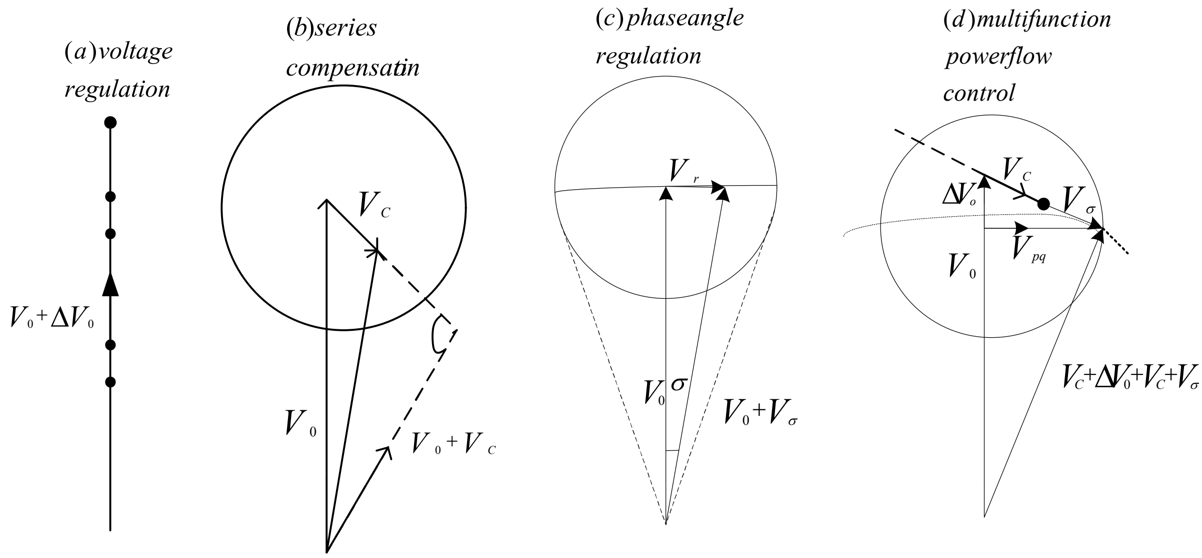


Fig 2.2 Basic UPFC control function. (a)Voltage Regulation (b) Series compensation (c) Angle regulation (d) Multi-function power flow controller

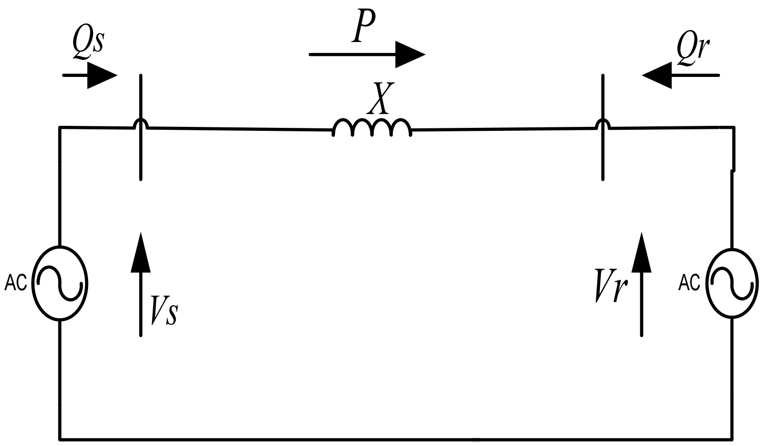
Terminal voltage regulation, similar to that obtainable with a transformer tap-changer having infinitely small steps, is shown at (a) where $V_m = \Delta V$ (boldface letters represent phasors) is injected in-phase (or anti-phase) with V_o. Series capacitive compensation is shown at (b) where $V_m = V_c$ is injected in quadrature with the line current I. Transmission angle regulation (Phase shifting) is shown at (c) where $V_{pq} = V_\sigma$ is injected with an angular relationship with respect to V_0that achieves the desired σphase shift (advance or retard) without any change in magnitude.

The fig (d) shows that Multi power flow control, executed by simultaneous terminal voltage regulation, series capacitive line compensation, and phase shifting, where $V_{pq} = \Delta V + V_c + V_\sigma$.

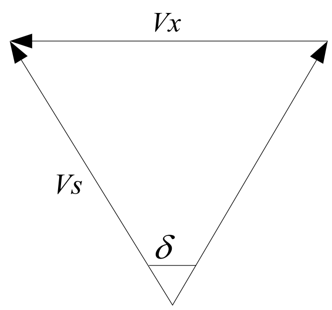
The powerful, hitherto unattainable, the capability of the UPFC summarized above in terms of conventional transmission control concepts, it can be integrated into a generalized power flow controller which is able to maintain prescribed, and independently controllable, the real power P and reactive power Q in the line. Within this concept, the conventional terms of series compensation, phase shifting etc., become irrelevant; the UPFC simply can controls the magnitude and angular position of the injected voltage in real time so as to maintain or vary the real and reactive power flow in the line.

2.5 Active and Reactive Power Control by UPFC:

In figure (2.3) a simple two machine (or two bus ac inertia) system with sending-end voltage V_s, receiving-end voltage V_r, and line (or tie) impedance X (assumed, for simplicity, inductive) is shown. At (b) the voltages of the system in form of a phasor diagram are shown with transmission angle δ and $V_s = V_r = V$. At the receiving ends of the line the transmitted active and reactive power are P=$\left\{\frac{V^2}{X}\right\}\sin\delta$ and Q =$Q_s = Q_r$=$\left\{\frac{V^2}{X}\right\}(1-\cos\delta)$.



(a)



(b)

Fig 2.3 (a) Simple two machine system (b) Related voltage phasors

The basic power system of Fig.2.3 with the known transmission characteristics is introduced to providing a vehicle to establish the capability of the UPFC to control the transmitted real power P and the reactive power demands, Q_s, and Q_r,at the sending-end and, respectively, the receiving-end of the line.

Consider Fig.2.4 where the simple power system of Fig2. 3 is expanded to include the UPFC. In the previous section explained that he UPFC is represented by a controllable voltage source in series with the line which, can generate or absorb reactive power that it negotiates with the line, but the real power it exchanges must be supplied to it, or absorbed from it, by the sending-end generator .The voltage which is injected by the UPFC in series with the line is represented by phasor V, having magnitude V_{pq} (0≤ V_{pq} ≤0.5 p. u) and angle ρ (0≤ρ ≤ 360°)measured from the given phase position of phasor as illustrated in the figure. The line current is represented by phasor I, flows through the series voltage source, V_{pq} and generally results in both reactive and real power exchange.

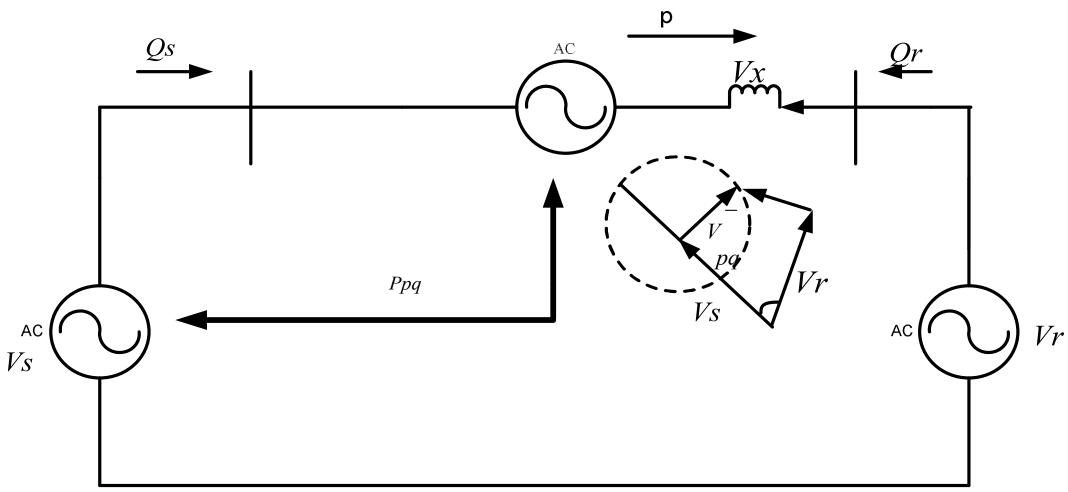


Fig 2.4 Two-machine system with the Unified Power Flow Controller

To represent the UPFC properly, the series voltage source is stipulated to generate only the reactive power Q, it exchanges with the line. Thus, the real power P, it negotiates with the line is assumed to be transferred to the sending end generator as if a perfect coupling for real power flow between it and the sending-end generator existed. It is an agreement with the UPFC circuit structure in which the dc link between the two constituent inverters establishes a bi-directional coupling for real power flow between the injected series voltage source and the sending end bus. As Fig.2.4 implies, in the present discussion it is further assumed for clarity that the shunt reactive compensation capability of the UPFC is not utilized. That is, shunt inverter is assumed that it's operated at unity power factor, its sole function being to transfer the real power demand of the series inverter to the sending- end generator. With these assumptions, series voltage source, together with the real power coupling to the sending-end generator as shown in Fig. 3.4, is an accurate representation of the basic UPFC.

It can be readily observed in Fig. 2.4 that the transmission line "sees" $V_s + V_{pq}$ as the effective sending-end voltage. Thus, it is clear that the UPFC affects the voltage (both its magnitude and angle) across the transmission line and therefore it is reasonable to expect that it is able to control, by varying the magnitude and angle of V_{pq} the transmittable real power as well as the reactive power demand of the line at any given transmission angle between the sending-end and receiving- end voltages. From fig 2.2(d)

$$V_{pq} = \Delta V + V_{\sigma} + V_q \tag{2.1}$$

$$\mathrm{P}-\mathrm{j}Q_r = V_r\left(\frac{V_s+V_{pq}-V_r}{jX}\right)^{*} \tag{2.2}$$

When V_{pq}=0 then

$$\mathrm{P}-\mathrm{j}Q_r = V_r\left(\frac{V_s-V_r}{jX}\right)^{*} \tag{2.3}$$

When $V_{pq}\neq 0$ then

$$\mathrm{P}-\mathrm{j}Q_r = V_r\left(\frac{V_s-V_r}{jX}\right)^{*} + \frac{V_r V_{pq}^{*}}{-jX} \tag{2.4}$$

Substituting

$$V_s = \mathrm{V}e^{j\delta/2} = \mathrm{V}\left(cos\frac{\delta}{2} + sin\frac{\delta}{2}\right) \tag{2.5}$$

$$V_r = \mathrm{V}e^{-j\delta/2} = \mathrm{V}\left(cos\frac{\delta}{2} - sin\frac{\delta}{2}\right) \tag{2.6}$$

And

$$V_{pq} = V_{pq}e^{-j(\delta/2+\rho)} = V_{pq}\left(cos(\frac{\delta}{2}+\rho) - sin(\frac{\delta}{2}+\rho)\right) \tag{2.7}$$

The following expressions are obtained for P and Q_r

$$P(\delta,\rho) = P_0(\delta) + P_{pq}(\rho) = \frac{V^2}{X}sin\,\delta - \frac{VV_{pq}}{X}cos\left(\frac{\delta}{2}+\rho\right) \tag{2.8}$$

$$Q_r(\delta,\rho) = Q_{r0}(\delta) + Q_{pq}(\rho) = \frac{V^2}{X}(1-cos\,\delta) - \frac{VV_{pq}}{X}sin\left(\frac{\delta}{2}+\rho\right) \tag{2.9}$$

Where $P_0(\delta) = \frac{V^2}{X}sin\,\delta$

and

$$Q_{r0}(\delta) = \frac{V^2}{X}(1-cos\,\delta) \tag{2.10}$$

Since angle ρ is freely varies between 0 and 2π at any given transmission angle δ (0≤δ≤π).It follows that $P_{pq}(\rho)$ and $Q_{pq}(\rho)$ are controllable between $-\frac{VV_{pq}}{X}$ and $+\frac{VV_{pq}}{X}$independent of angle δ .therefore the transmittable real power varies between

$$P_0(\delta) - \frac{VV_{pqmax}}{X} \le P_0(\delta) \le P_0(\delta) + \frac{VV_{pqmax}}{X} \tag{2.11}$$

and the reactive power varies between

$$Q_{r0}(\delta) - \frac{VV_{pqmax}}{X} \leq Q_{r0}(\delta) \leq Q_{0r}(\delta) + \frac{VV_{pqmax}}{X} \tag{2.12}$$

The normalized transmitted active power

$$P_0(\delta) = \frac{V^2}{X} sin\, \delta = sin\, \delta \tag{2.13}$$

And the normalized transmitted reactive power

$$Q_{r0}(\delta) = -\frac{V^2}{X}(1 - \cos\delta\,) = (1 - \cos\delta) \tag{2.14}$$

In general, at any given transmission angle δ**,** the transmitted real power P, and the reactive power demands at the transmission line ends, Qs and Qr , can be controlled freely by the UPFC.

The relationship between real power $P_0(\delta)$ and reactive power $Q_{r0}(\delta)$ can readily be expressed with $\frac{V^2}{X} = 1$ in the following form.

$Q_{r0}(\delta)$=-1$-\sqrt{1-\{P_0(\delta)\}^2}$

Or $\{Q_{r0}(\delta) - 1\}^2 + \{P_0(\delta)\}^2 = 1$ (2.15)

The above equation describes a circle with a radius of 1.0around the center defined by coordinates $P_0(\delta)$ and Q_r= -1 in a $\{Q_r$, P$\}$ plane. Each point of this circle gives the corresponding value of $P_0(\delta)$and $Q_{r0}(\delta)$values of the uncompensated system at a specific transmission angle δ.

Assume that$V_{pq} \neq 0$.that the real and reactive power change from their uncompensated values , $P_0(\delta)$and $Q_{r0}(\delta)$,as a function of magnitude Vpq and angle ρ of the injected voltage phasor Vpq Since angle ρ is an unrestricted variable (0≤ ρ≤2π),The boundary of the attainable control region for P$(\delta,\rho)$and$Q_r(\delta,\rho)$ is obtained from a complete rotation of phasor Vpq with its maximum magnitude V_{pqmax}.It follows from the above equation that this control region is a circle with a center defined by coordinates $P_0(\delta)$ and $Q_{r0}(\delta)$ and radius of $\frac{V_r V_{pq}}{X}$

The boundary can be described by the following equation:

$$\{P(\delta,\rho) - P_0(\delta)\}^2 + \{Q_r(\delta,\rho) - Q_{r0}(\delta)\}^2 = \left\{\frac{VV_{pqmax}}{X}\right\}^2 \tag{2.16}$$

At any given transmission angle δ, the transmitted real power P, and the reactive power demands at the transmission line ends, Q_s and Q_r , can be controlled freely by the UPFC within the boundaries obtained in the $\{Q_s$,P$\}$ and $\{Q_r$,P$\}$.

Chapter 3

POWER INJECTION MODEL OF UPFC

3.1 **Series Connected Voltage Source Converter Model:**

A model for UPFC which will be referred as UPFC injection model is derived .In this model UPFC can be represented in the steady-state by two voltage sources representing fundamental components of output voltage waveforms of the two converters and impedances being leakage reactance of the two coupling transformers. This model is helpful in understanding the impact of the UPFC on the power system in the steady state. Furthermore, the UPFC injection model can easily be incorporated in the steady state power flow model.

Since the series voltage source converter does the main function of the UPFC, it is appropriate to discuss the modeling of a series voltage source converter first. Figure 3.1 Representation of a series connected VSC. Voltage of bus i is taken as reference vector, $V_i = V_i < \theta_i$and

$$\bar{V}_i^{/}=V_s + V_i \tag{3.1}$$

. The voltage sources, $V_s$and is controllable in both their magnitudes and phase angles.

Here $V_s = rV_i e^{j\gamma}$. (3.2)

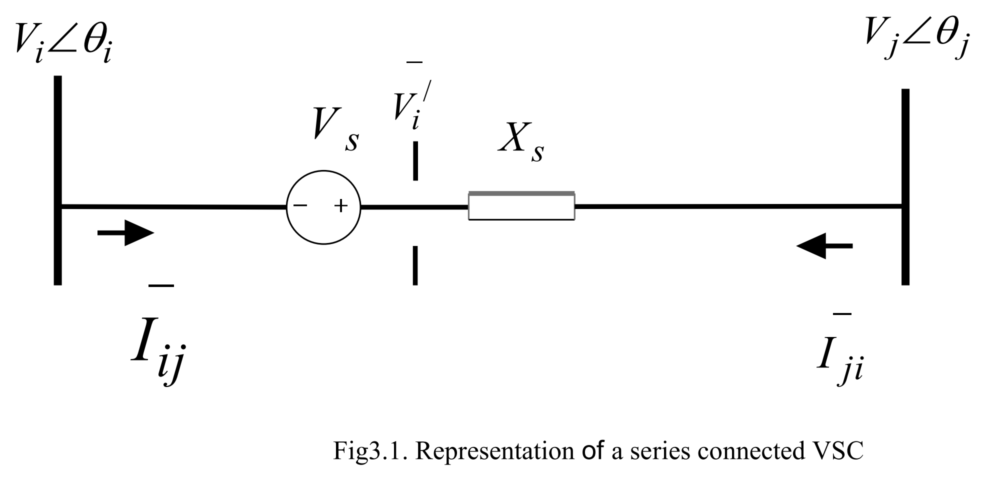


Fig3.1. Representation of a series connected VSC

The values of r and $\gamma$are defined within specified limits given by as $0 \leq r \leq r_{max}$ and $0 < \gamma < 2\pi$.

The steady-state UPFC mathematical model is developed by replacing voltage sourceV_s by a current source $I_s$parallel with the transmission line, where b_s=$\frac{1}{x_s}$.where

I_s = -j$b_s V_s$ (3.3)

The current source $I_s$can be modeled by injection powers at the two auxiliary buses i and j as shown in Figure3.2

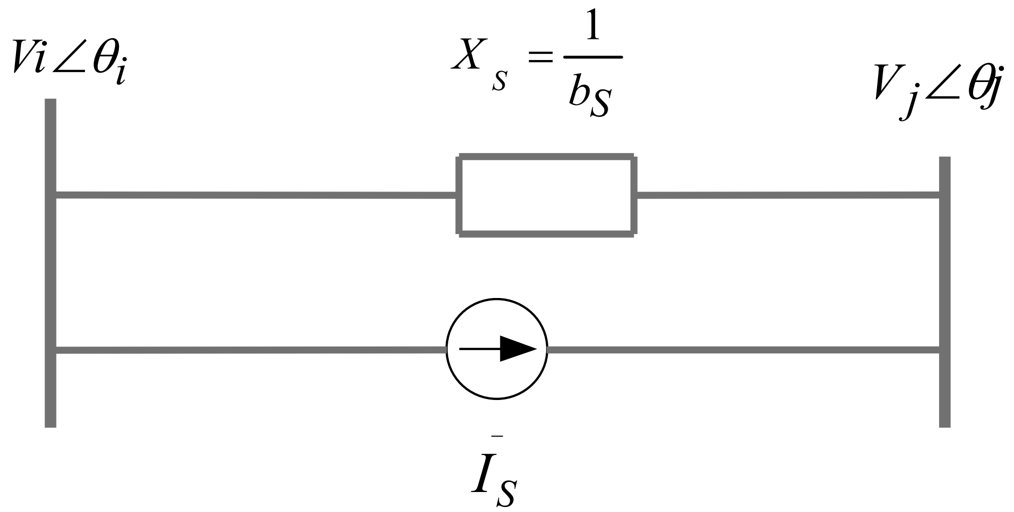


Fig**3**.2. Replacement of series voltage source by a current source.

The current sources $I_s$corresponds to the injection powers$S_{is}$and S_{js} , where

$S_{is} = V_i(-I_s)^*$ (3.4)

S_{js}=$V_j(I_s)^*$ (3.5)

The injection power $\overline{S_{\iota s}}$ and $\overline{S_{\jmath s}}$can be simplified according to the following operations, by substituting Equation (3.2) and (3.3) into Equation (3.4) and (3.5) as

$S_{is} = V_i\left[jb_s rV_i e^{j\gamma}\right]^*$ (3.6)

By using the Euler Identity, ($e^{i\gamma} = cos\,\gamma + jsin\,\gamma$) , Equation (3.6) takes the form:

$S_{is} = V_i\left[e^{j(\gamma+90)} b_s\, r\, V_i^*\right]$

$S_{is} = V_i^2 b_s r[cos(-\gamma - 90) + j\,sin(-\gamma - 90)]$ (3.7)

By using trigonometric identities, Equation (3.7) reduces to:

$= -b_s rV_i{}^2\, sin\,\gamma - jb_s V_i{}^2\, cos\,\gamma$ (3.8)

If we define:$\theta_{ij} = \theta_i - \theta_j$

Similar modifications can be applied to Equation (3.5);

$$S_{js} = V_j\left[-jb_s r V_j e^{j\gamma}\right]^* ;$$

The final equation takes the form

$$= b_s r V_i V_j \sin(\theta_{ij} + \gamma) + j\, b_s r V_i V_j \qquad (3.9)$$

Now after decomposed the equations (3.8) and (3.9) into its real and imaginary parts**,** the injection model of a series connected voltage source can be seen as two dependent loads as shown in Fig 3.3

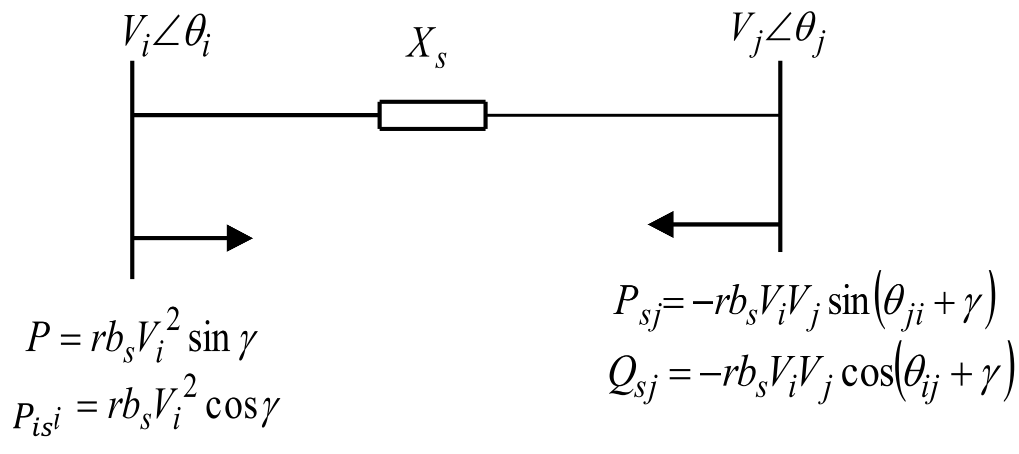


Fig.3.3 Injection model for a series connected VSC

3.2 Shunt converter model

Converter1 is used mainly to provide the active power, which is injected to the system via the series connected voltage source. When the losses are neglected

$$P_{con1} = P_{cov2} \qquad (3.10)$$

The apparent power supplied by the series voltage source converter is

$$S_{conv2} = V_s I_{ij}^* = re^{j\gamma} V_i \left(\frac{\bar{V}_i' - V_j}{jX_s}\right)^* \qquad (3.11)$$

$=\mathrm{r}e^{j\gamma}V_i((re^{j\gamma}V_i + V_i - V_j)/jX_s\,)^*$

After simplification, the active and reactive powers supplied by converter2 are

$$P_{con2} = rb_sV_iV_j \sin(\theta_i - \theta_j + \gamma) - rb_sV^2{}_i \sin\gamma \qquad (3.12)$$

$$Q_{con2} = -rb_sV_iV_j \cos(\theta_i - \theta_j + \gamma) + rb_sV^2{}_i \cos\gamma + r^2 b_s V^2{}_i \qquad (3.13)$$

Delivered or absorbed of the reactive power by converter 1 is independently controllable by UPFC and can be modeled as a separate controllable shunt reactive source. In that case the main function of reactive power is to maintain the voltages level at bus ‘i’ within acceptable limits. In view of above, we assume that $Q_{conv1} = 0$(In above the possibility to control $Q_{conv1}$is investigated). Consequently, the UPFC injection model construed from the series Connected voltage source model (Fig. 3.3) with the addition of a power equivalent to $\boldsymbol{P}_{conv1} + j0$ to node i.

Finally, steady-state UPFC mathematical model can be constructed by combining the series and shunt power injections at both bus ‘i’ and bus ‘j’ as shown in Figure 3.4.

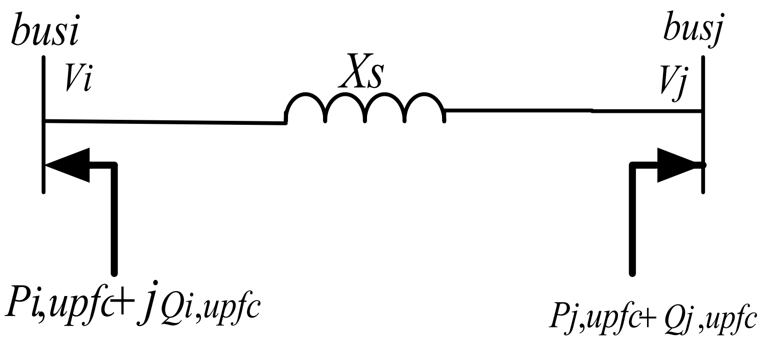


Fig 3.4 Steady-state complete UPFC mathematical model

The elements of the equivalent power injections in Figure 3.4 are,

$$P_{i,upfc} = rb_s V^2{}_i sin\,\gamma \text{-} rb_s V_i V_j \,sin(\theta_i - \theta_j + \gamma) \quad (3.14)$$

$$P_{j,upfc} = rb_s V_i V_j \,sin(\theta_i - \theta_j + \gamma) \quad (3.15)$$

$$Q_{i,upfc} = -rb_s V^2{}_i cos\,\gamma \quad (3.16)$$

$$Q_{j,upfc} = rb_s V_i V_j \,cos(\theta_i - \theta_j + \gamma) \quad (3.17)$$

3.3 UPFC Injection Model for Load Flow Studies:

3.3.1 Load flow studies

The load flow studies are the backbone of the power system analysis and design. They are used for planning, operation, economic scheduling, exchange of power between utilities and stability analysis.

- The analysis of power flow is very important in planning stages of new networks or addition to existing ones like adding new generator sites, increase load demand and locating new transmission sites.
- Load flow solution gives the nodal voltages and phase angles and hence the power injection at all the buses and power flows through interconnecting power channels.
- The load flow is used to determine the best location as well as optimal capacity of proposed generating station, substation and new lines.
- It's used to determine the voltage of the buses. The voltage level of the buses must be kept within the closed tolerances.
- To minimize the transmission line losses.
- Economic consideration with respect to fuel cost to generate all the power needed.
- To study about the stability of power system.

3.3.2. Bus Classification

In a power system a bus is a node at which one or many lines, one or many loads and generators are connected. Each node or bus is associated with 4 quantities, as magnitude of voltage, phage angle of voltage, true or active power and reactive power in load flow problem, out of these 4 quantities two are specified and remaining 2 are required to be determined through the solution of equation. Depending on these quantities that have been specified, the buses are can be classified into 3 categories.

Buses are classified according to which two out of the four variables are specified as

3.3.2.1 Slack Bus

A swing bus (or slack bus) is a generator bus with a generator controlling the terminal voltage, V_t, and angle delta, δ, at the bus. It is also known as a reference bus. The terminal voltage angle would typically be set at 0° with the voltage set at 1 per unit (p.u.) voltage. The terminal voltage is kept constant by adjusting the field current in the generator. With V_t and the angle delta being known parameters for this bus, the two unknown parameters are the real power P, and the reactive power Q. The slack bus makes up the difference between the scheduled loads and generated power that is caused by the losses in the networks. This machine swings or takes up the slack; hence it fits its name.

3.3.2. 2 Generator Bus

A generator or PV bus in which a generator is connected with it .A synchronous generator controlling the terminal voltage and real power supplied to the bus. The terminal voltage is kept constant by adjusting the field current in the generator. At the same time, this also changes the reactive power supplied by the generator to the system. The prime mover controls the power the generator supplies the system. The generator on this bus has a set amount of real power, P, it provides at or near its capacity. These generators work most efficiently at full capacity. Rest of the real power is picked up by the Swing Bus generator. The P and the V_t are the two known parameters for this bus type. The reactive power Q, and the angle delta, δ are the two unknown parameters for this type of bus.

3.3.2.3 Load Bus

A load bus or PQ bus in which the real and reactive power are scheduled or connected. There are no generators are connected with them. The known parameters for this type bus are real power (P), and reactive power (Q). The unknown parameters are the voltage magnitude |V|, and angle delta δ.

There are three methods for load flow studies mainly:
#Gauss siedel method
Newton raphson method
Fast decoupled method

The two most commonly used iterative techniques, namely are Gauss-Seidel and Newton-Raphson methods for solution of nonlinear algebraic equations. The Gauss-Seidel method is known as the method of the successive displacements. To solve by this method needs much iteration to achieve the desired accuracy, but no guarantee for convergence.

The most widely used method for solving simultaneous nonlinear algebraic equation is Newton-Raphson method .This method is successive approximation procedure based on an initial estimate of the unknown and the use of Taylor's series expansion. For the large power systems, the Newton-Raphson is more efficient and practical. The number of iteration required to obtain a solution is independent of the system size, but more functional evolutions are required at each iteration .

The power flow equations are

$$P_i = \sum_{j=1}^{n} |V_i|\,|V_j|\,|Y_{ij}|\,cos(\theta_{ij} - \theta_i + \theta_j) \quad (3.18)$$

$$Q_i = -\sum_{j=1}^{n} |V_i|\,|V_j|\,|Y_{ij}|\,sin(\theta_{ij} - \theta_i + \theta_j) \quad (3.19)$$

Equations (18) and (19) constitute a set of non linear algebraic equations in terms of independent variables; voltage magnitude is in per unit, and phase angle is in radians. After expanding (18)&(19) in Taylor's series about the initial estimate and neglecting all higher terms result, in sort form it can be written as,

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ J & L \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V/_V \end{bmatrix} \quad (3.20)$$

3.5 Modification of Jocobian Matrix:

From the Steady-state UPFC model, the general nodal power flow equations and the linear zed power system model can be expressed in rectangular form by the following equations.

$$P = f_1(V, \theta, G, B) \quad (3.21)$$

$$Q = f_1(V, \theta, G, B) \quad (3.22)$$

Where P and Q are the vectors of real and reactive nodal power injections, which are function of nodal voltages,($V < \theta$), and network conductance's and susceptance's, (G and B), respectively. ($\Delta P = P_{spe} - P_{cal}$) is the real power mismatch vector and ($\Delta Q = Q_{spe} - Q_{cal}$) is the reactive power mismatch vector. ($\Delta V\ and\ \Delta\theta$) are vectors of incremental changes in nodal voltages. H, N, J and L are denoting the basic elements in the Jacobian matrix. They correspond to partial derivatives of the real and the reactive powers, with respect to the phase angles and the magnitudes of the nodal voltages; The derived injected power model can be incorporated into a general NR power flow algorithm by modifying the related elements in the normal Jacobian matrix and the corresponding power mismatch equations as well. Since injected powers vary with bus bar voltage amplitudes and phases, the relevant elements of Jacobian matrix will be modified. The elements of $H^{org}$and N, J and L can be derived from (3.21 and 3.22). Based on equation (3.21–3.22), the following additional elements of

Jacobian matrix $H_{upfc}$and for *N*, *J*, and *L* (table: 1) owing to the injections of the UPFC at the buses 'i' and 'j' can be derived.

For bus 'i', when i=j,

$$H_{ii}^{upfc}=\frac{\delta P_i}{\delta \theta_i}$$

$$N_{ii}^{upfc}=V_i\frac{\delta P_i}{\delta V_i}$$

$$J_{ii}^{upfc}=\frac{\delta Q_i}{\delta \theta_i}$$

$$L_{ii}^{upfc}=V_i\frac{\delta Q_i}{\delta V_i}$$

When i≠j $\qquad H_{ij}^{upfc}=\frac{\delta P_i}{\delta \theta_j}$

$$N_{ij}^{upfc}=V_j\frac{\delta P_i}{\delta V_j}$$

$$J_{ij}^{upfc}=\frac{\delta Q_i}{\delta \theta_j}$$

$$L_{ij}^{upfc}=V_j\frac{\delta Q_i}{\delta V_j}$$

For bus j, when i=j, $\qquad H_{jj}^{upfc}=\frac{\delta P_j}{\delta \theta_j}$

$$N_{jj}^{upfc}=V_j\frac{\delta P_j}{\delta V_j}$$

$$J_{jj}^{upfc}=\frac{\delta Q_j}{\delta \theta_j}$$

$$L_{jj}^{upfc}=V_j\frac{\delta Q_j}{\delta V_j}$$

When i≠j $\qquad H_{ji}^{upfc}=\frac{\delta P_j}{\delta \theta_i}$

$$N_{ji}^{upfc}=V_j\frac{\delta P_j}{\delta V_i}$$

$$J_{ji}^{upfc}=\frac{\delta Q_j}{\delta \theta_i}$$

$$L_{ji}^{upfc}=V_j\frac{\delta Q_j}{\delta V_i}$$

Table 1 shows the modification jacobian matrix with UPFC. In this table the Superscript ° denotes the Jacobian elements without UPFC. The Superscript $upfc$ denotes the Jacobian elements with UPFC.

Table 1: Modification of Jacobian matrix

$H_{(i,i)} = H°_{(i,i)} + H_{ii}^{upfc}$ $H_{(i,j)} = H°_{(i,j)} + H_{ij}^{upfc}$ $H_{(j,i)} = H°_{(j,i)} + H_{ji}^{upfc}$ $H_{(j,j)} = H°_{(j,j)} + H_{jj}^{upfc}$	$N_{(i,i)} = N°_{(i,i)} - N_{ii}^{upfc}$ $N_{(i,j)} = N°_{(i,j)} - N_{ij}^{upfc}$ $N_{(j,i)} = N°_{(j,i)} + N_{ji}^{upfc}$ $N_{(j,j)} = N°_{(j,j)} + N_{jj}^{upfc}$
$J_{(i,i)} = J°_{(i,i)} + J_{ii}^{upfc}$ $J_{(i,j)} = J°_{(i,j)} + J_{ij}^{upfc}$ $J_{(j,i)} = J°_{(j,i)} - J_{ji}^{upfc}$ $J_{(j,j)} = J°_{(j,j)} + J_{jj}^{upfc}$	$L_{(i,i)} = L°_{(i,i)} - L_{ii}^{upfc}$ $L_{(i,j)} = L°_{(i,j)} + L_{ij}^{upfc}$ $L_{(j,i)} = L°_{(j,i)} + L_{ji}^{upfc}$ $L_{(j,j)} = L°_{(j,j)} + L_{jj}^{upfc}$

Chapter 4

RESULTS AND DISCUSSION

To observe the steady state performance of the UPFC in the power, three standard study systems are taken. IEEE 30 bus, IEEE14 bus and IEEE5 bus systems has taken.

4.1 IEEE 30 Bus system:

Base MVA=100;

$X_s = 0.025;$

Total active power loss without UPFC=19.114MW;

Total reactive power loss without UPFC= 36.091MVA;

After incorporating UPFC in the system the active and reactive power losses are given in table 2.When UPFC is incorporated in between two buses and for different value of 'r' and'γ '$= 120°$ the variation of active and reactive power losses are shown.From the table we observed that when UPFC is incorporated in the system the active and reactive power loss in the transmission line has reduced. It is also observed that least power losses occurred when UPFC is incorporated in between bus 10-17.

Table 2: Active& reactive power losses for different value of 'r' and 'γ' in various buses

When r=0.01 &$\gamma = 120°$			*When r=0.04 &*$\gamma = 120°$			*When r=0.06&*$\gamma = 120°$		
Line	P_{loss}	Q_{loss}	*Line*	P_{loss}	Q_{loss}	*Line*	P_{loss}	Q_{loss}
6-7	19.034	35.051	*6-7*	18.902	31.740	*6-7*	18.99	31.688
3-4	19.076	35.954	*3-4*	18.834	33.801	*3-4*	18.715	32.65
4-6	19.108	36.068	*4-6*	19.111	36.079	*4-6*	19.00	34.932
12-14	19.116	36.101	*12-14*	19.112	36.081	*12-14*	18.898	34.367
12-15	19.114	36.093	*12-15*	19.119	36.120	*12-15*	19.102	36.05
12-16	19.081	35.908	*12-16*	N.C	N.C	*12-16*	N.C	N.C
14-15	19.046	35.742	*14-15*	210.836	647.015	*14-15*	N.C	N.C
16-17	19.059	35.829	*16-17*	203.055	1006.643	*16-17*	N.C	N.C

15-18	19.094	35.99	*15-18*	19.107	36.057	*15-18*	18.607	32.898
18-19	19.029	35.69	*18-19*	18.887	34.105	*18-19*	18.674	32.474
19-20	19.036	35.727	*19-20*	18.767	33.552	*19-20*	N.C	N.C
10-20	18.972	34.703	*10-20*	18.566	30.730	*10-20*	19.623	30.923
10-17	18.959	34.645	*10-17*	18.554	30.677	*10-17*	19.623	30.920
10-21	19.115	36.034	*10-21*	19.115	36.098	*10-21*	19.119	36.118
15-23	19.72	35.881	*15-23*	184.397	585.468	*15-23*	244.114	1049.366
23-24	19.07	35.881	*23-24*	19.051	35.761	*23-24*	180.880	579.621
22-24	19.094	36.019	*22-24*	19.029	35.019	*22-24*	18.691	32.665
25-27	19.087	35.365	*25-27*	19.106	36.054	*25-27*	N.C	N.C
24-25	19.081	35.938	*24-25*	18.968	34.688	*24-25*	N.C	N.C
25-26	18.954	34.907	*25-26*	N.C	N.C	*25-26*	N.C	N.C
8-28	19.114	36.91	*8-28*	19.113	36.086	*8-28*	19.109	32.665
6-28	19.114	36.091	*6-28*	19.114	36.092	*6-28*	19.115	36.093
25-27	19.087	35.965	*25-27*	19.106	36.054	*25-27*	N.C	N.C
28-27	19.116	36.093	*28-27*	19.107	36.074	*28-27*	N.C	N.C
27-29	19.111	36.082	*27-29*	N.C	N.C	*27-29*	N.C	N.C
27-30	19.116	36.102	*27-30*	67.475	194.436	*27-30*	N.C	N.C
6-9	19.114	36.089	*6-9*	19.116	36.117	*6-9*	19.11	36.022
4-12	19.088	36.003	*4-12*	18.833	33.801	*4-12*	18.764	33.566
29-30	19.102	36.050	*29-30*	67.391	193.938	*29-30*	67.595	192.633

N.C-Not Converge

The Voltage performances of the various buses are shown in figure 4.1, 4.2 and 4.3 after incorporating UPFC and without UPFC .In fig 4.1 shown that when ‘r’=0.04, ‘γ’=120° and UPFC is incorporated between in buses 6-7 ,the bus voltages are improved. In fig 4.2 and fig 4.3 also shown bus voltages are improved when ‘r’=0.04, ‘γ’=120° and UPFC is incorporated between in buses 10-17 and 19-20 respectively. But Fig4.4 shows that voltage profile of the various buses decreases due to incorporate UPFC in between buses 29-30 when ‘r’=0.04, ‘γ’=120°.Its tells us that theoretically the UPFC can incorporate anywhere in the system but in practically its cannot be incorporated anywhere in the transmission line.

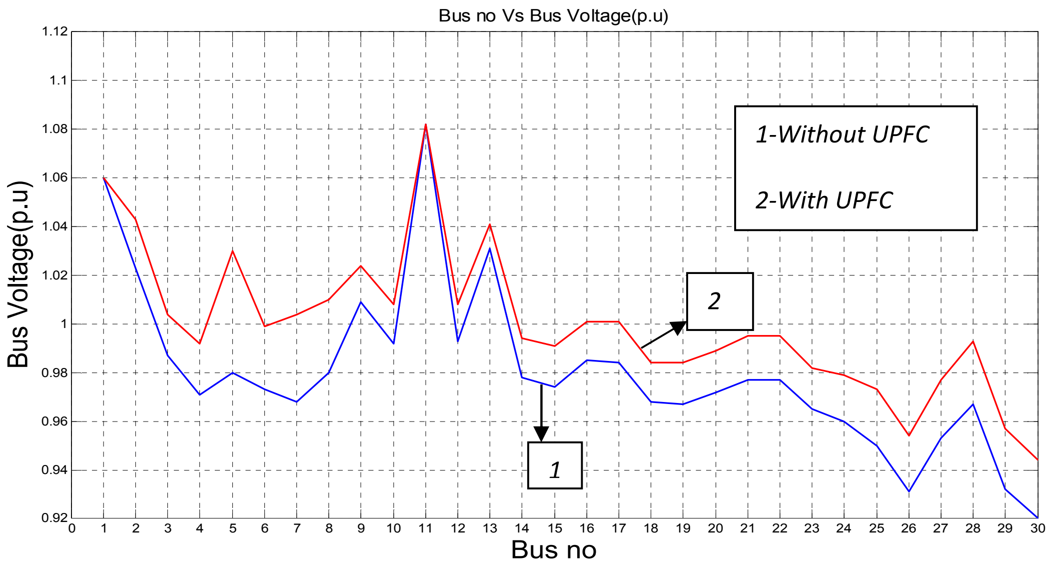


Fig4.1: Bus voltage increased after incorporate UPFC in between buses 6-7

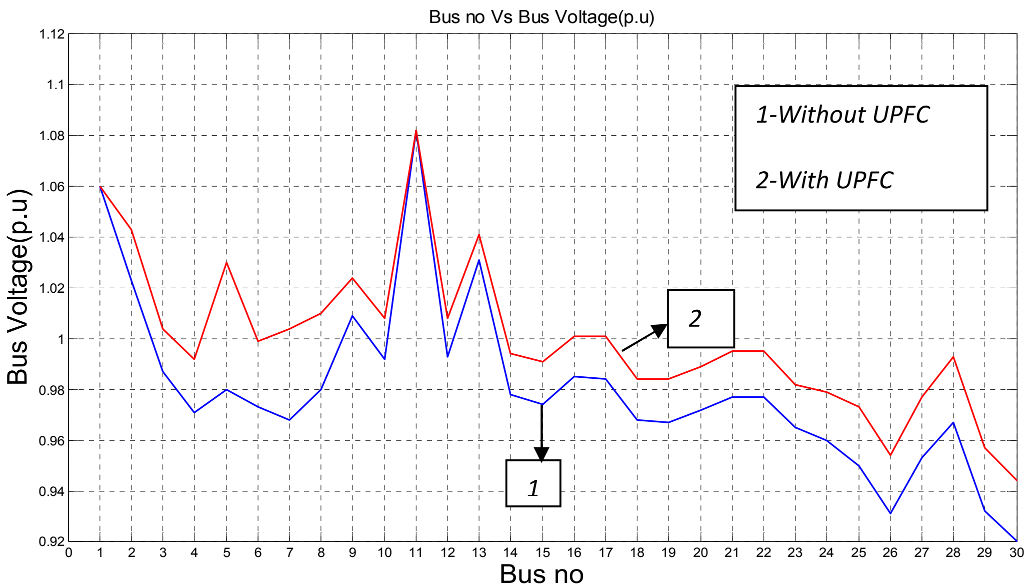


Fig4.2: Bus voltage increased after incorporate UPFC in between buses 10-17

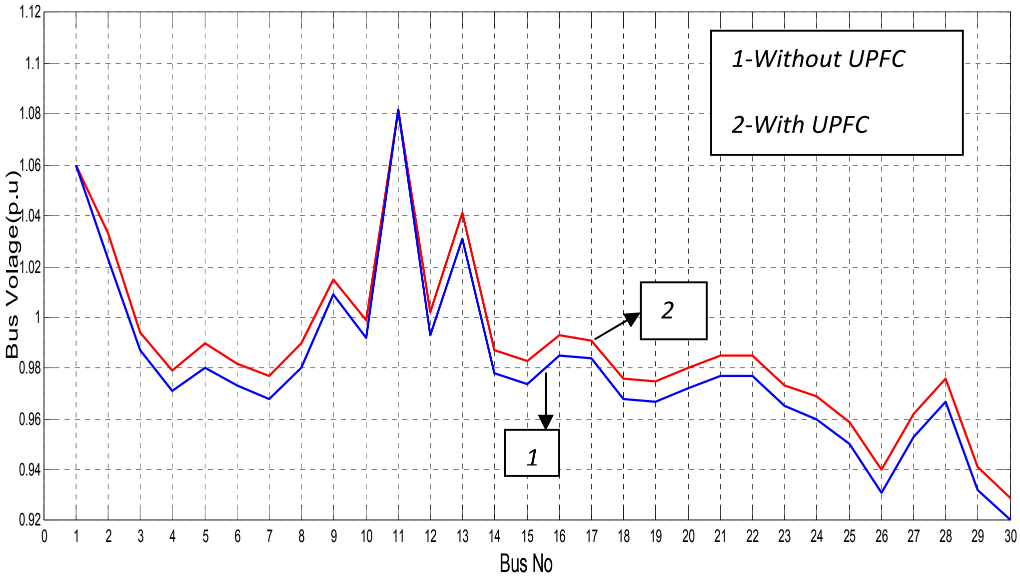


Fig4.3: Bus voltage increased after incorporate UPFC in bus 19-20

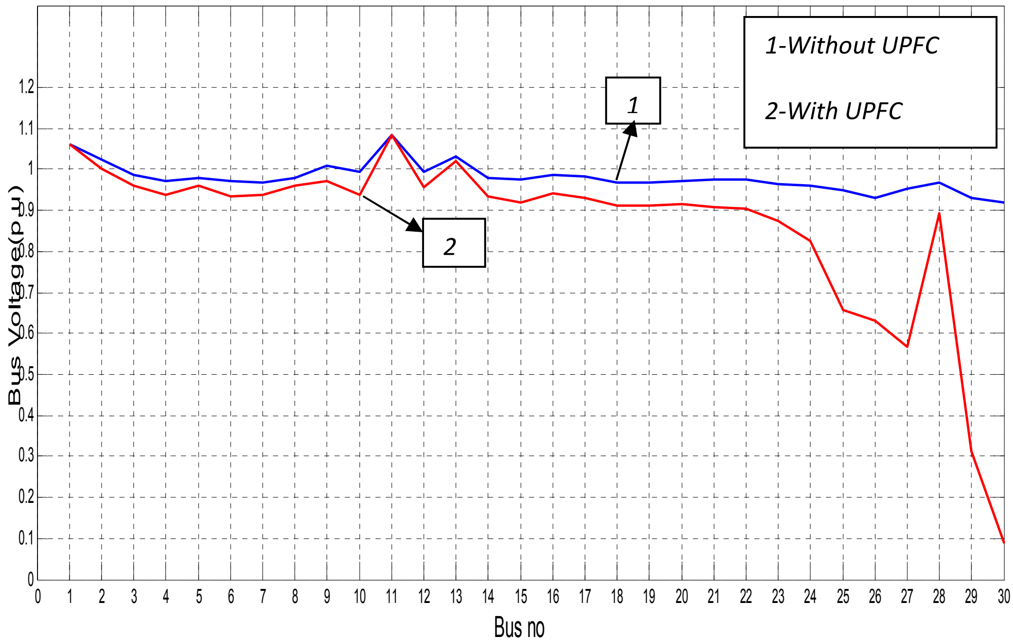


Fig4.4: Bus voltage decreased after incorporate UPFC in between buses 29-30

In fig 4.5 and fig4.6 shows the variation of active and reactive power losses for the different value ‘r’, at gamma=120° when UPFC is incorporated in 10-17.From the fig 4.5 and 4.6 we observed that when the value of ‘r’ is increased up to a certain value the active and reactive power losses are reduced but after that the program does not exist.

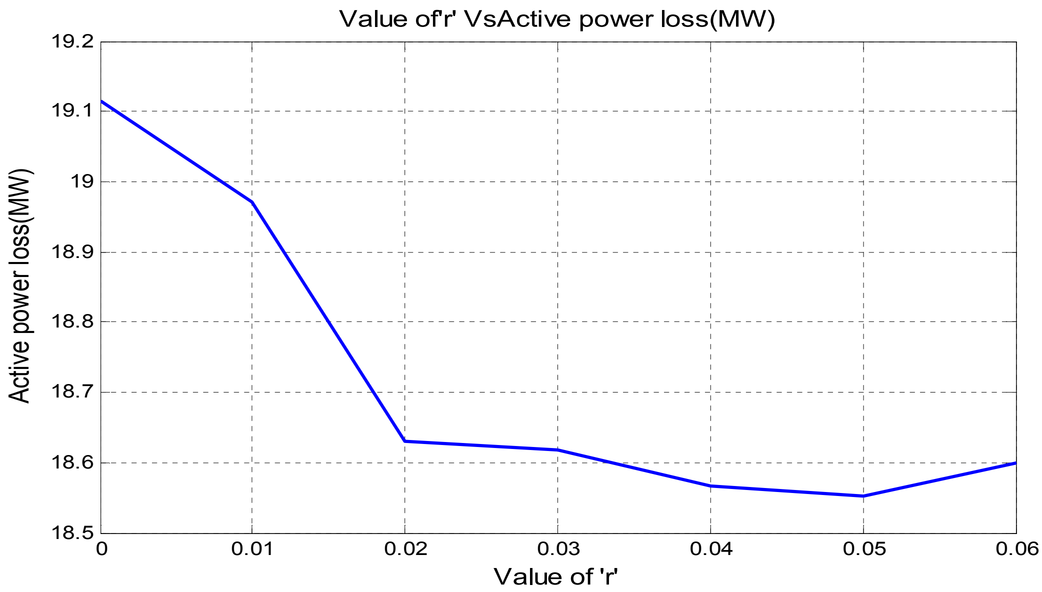


Fig.4.5.Active power losses for different value or ‘r’ at’ γ’=120°

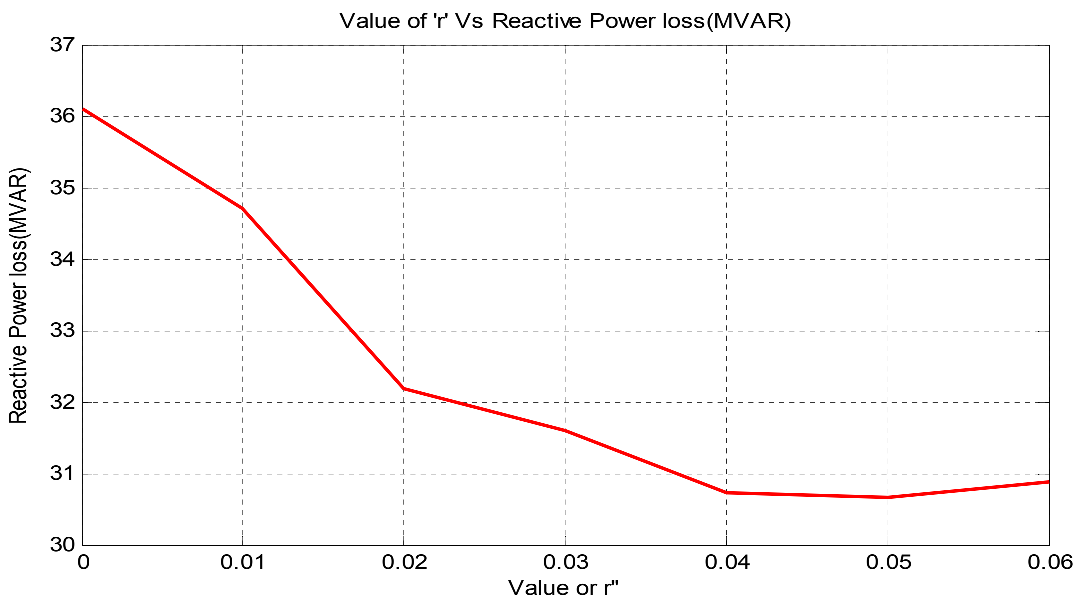


Fig.4.6.Reactive power losses for different value or ‘r’ at’ γ’=120°

The Fig.4.7and 4.8 shows the variation of active and reactive power losses at ‘r’=0.04 and for the different value of gamma, when UPFC is incorporated in 10-17. From fig4.7 and 4.8 we observed that for a constant value ‘r’=0.04 if ‘γ’ is increased the active and reactive power losses also increased.

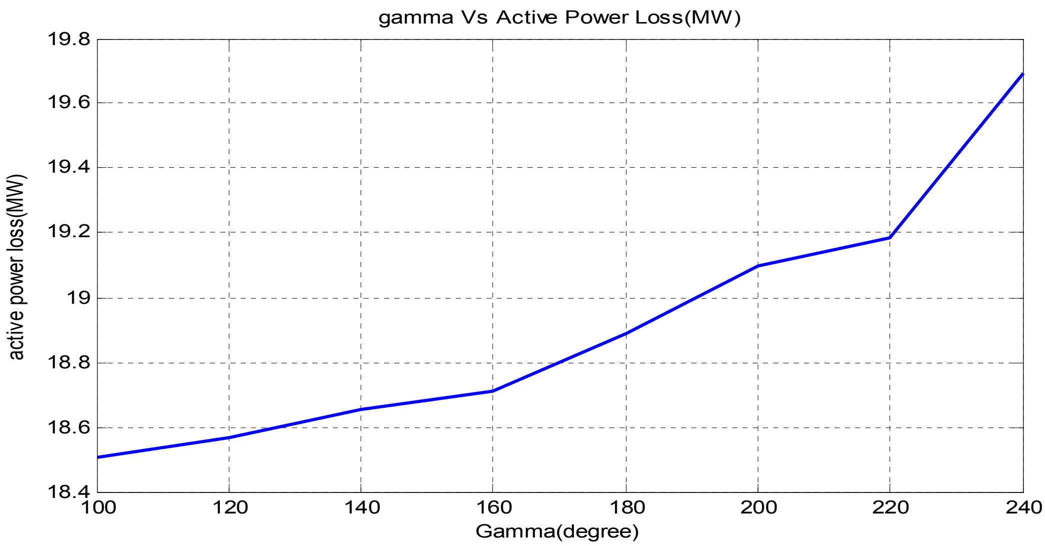


Fig.4.7. Active power losses for different value or ‘γ’ (degree) at ‘r’=0.04

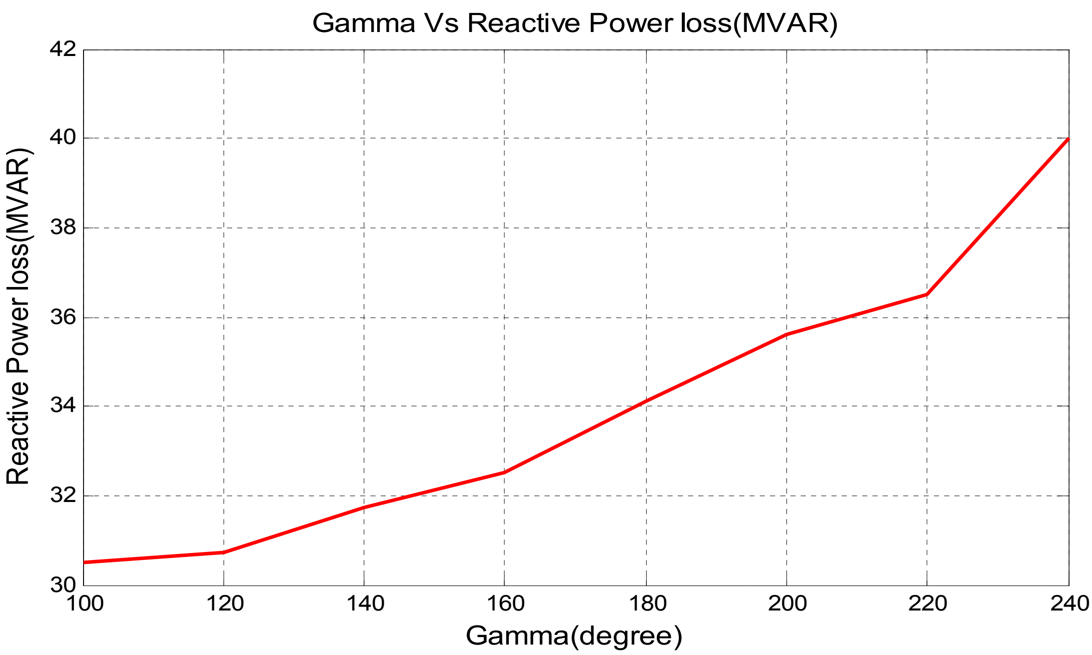


Fig.4.8. Reactive power losses for different value or ‘γ’ (degree) at ‘r’=0.04

4.2 IEEE 14 Bus system:

IEEE 14 bus system has taken to test.

Base MVA=100;

Total active power loss without UPFC=43.22 7MW

Total reactive power loss without UPFC=173.014 MVA

The table 3 shows that variation of active and reactive power losses after incorporating the UPFC in between two buses in the system. Two cases are considered. At first case when 'r'=0.055, 'γ'=180°and the UPFC is in between two buses like 4-6,4-7 are shown .At that time the active and reactive power losses are measured. Another case is considered when 'r'=0.04 and 'γ'=140°.From the both cases we can say that when the UPFC is in 9-10, the least power losses occurred.

Table 3: Active& reactive power losses for different value of 'r' and 'γ

When r=0.055& $\gamma = 180°$			When r=0.04&γ=140°		
Line	P_{loss}(MW)	Q_{loss}(MVAR)	*Line*	P_{loss}(MW)	Q_{loss}(MW)
4-5	43.228	173.018	*4-5*	43.227	173.015
4-7	43.225	173.014	*4-7*	43.226	173.014
4-9	41.528	166.837	*4-9*	41.785	167.063
7-9	41.525	166.809	*7-9*	41.524	166.806
9-10	41.254	166.537	*9-10*	41.528	166.802
9-14	N.C	N.C	*9-14*	N.C	N.C
10-11	N.C	N.C	*10-11*	44.439	170.512
12-13	41.793	167.094	*12-13*	43.228	173.023
13-14	43.227	173.014	*13-14*	43.102	172.886

The fig 4.11 and 4.12 shows the variation of the active and reactive power losses for various values of ‘r’ and constant ‘γ’=140° when UPFC is incorporated in 7-9.From fig 4.11 we observed that for a constant value of ‘γ’=140° if ‘r’ is increased the active power loss is reduced up to a certain value after that the program does not exist. In figure 4.12 also shows that that for a constant value of ‘γ’=140° if ‘r’ is increased the reactive power loss is reduced.

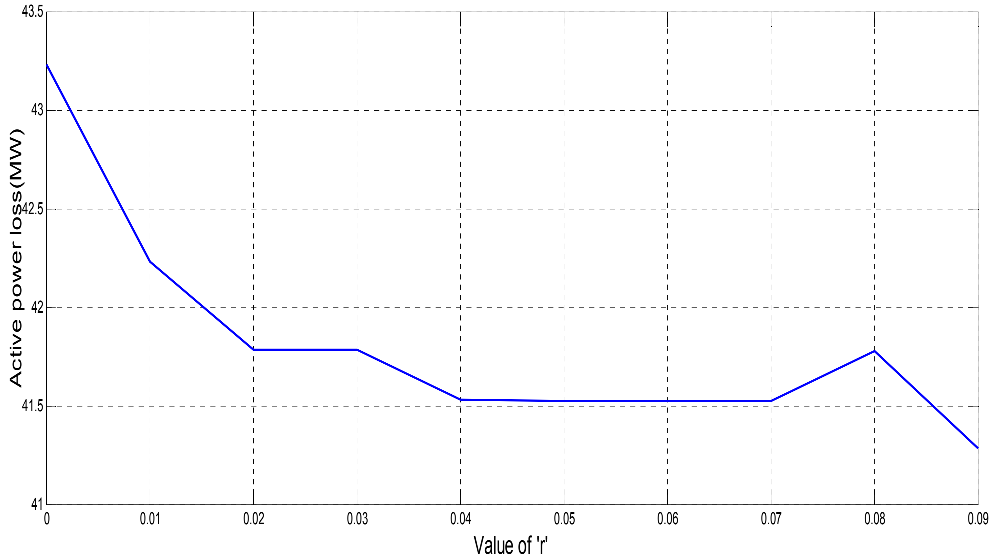


Fig 4.9Variation Active power loss for different value or ‘r’ at ‘γ’=140°’

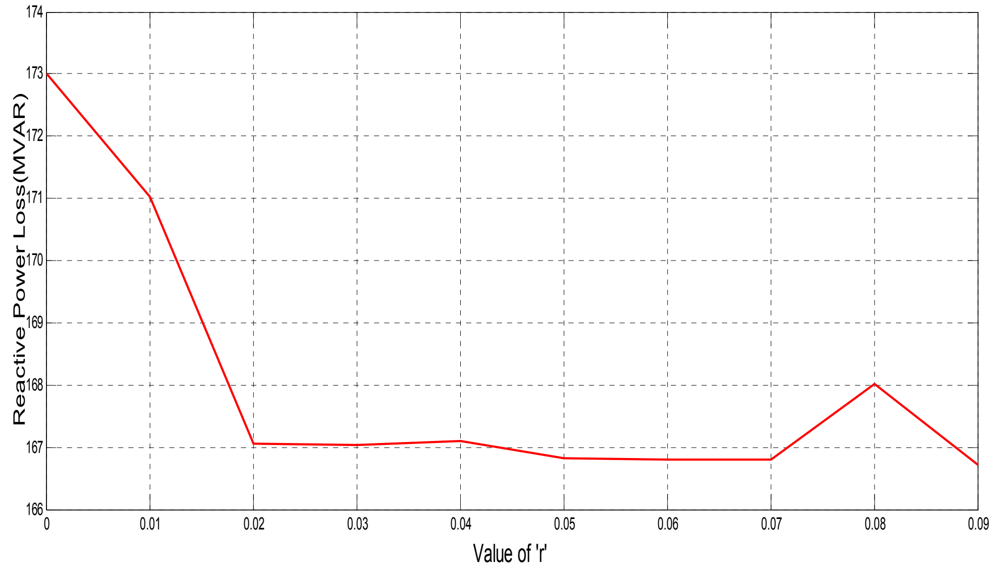


Fig.4.10Variation of Reactive power loss for different value or ‘r’ at ‘γ’=140°

For a constant value of ‘r=0.04 and for various value of‘γ’ the variation of active and reactive power losses are shown fig4.13 and 4.14.The UPFC is corporate is in 7-9. From fig4.13 and 4.14 we observed that for a constant value ‘r’=0.04 if ‘γ’ is increased then the active and reactive power losses also increased. If the value of ‘γ’ increased after 260° the program does not exist.

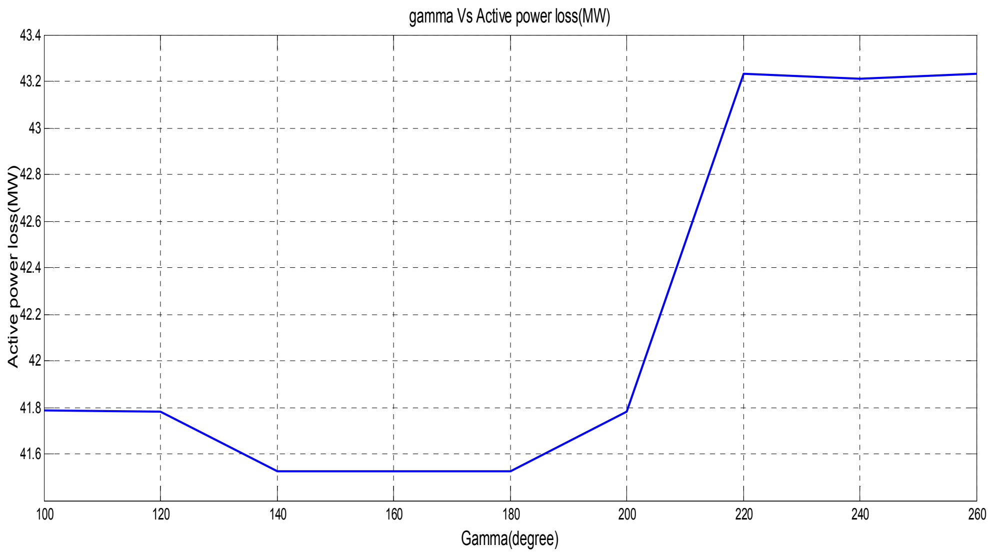


Fig.4.11Variation of Active power loss for different value or ‘γ’ at ‘r’=0.04

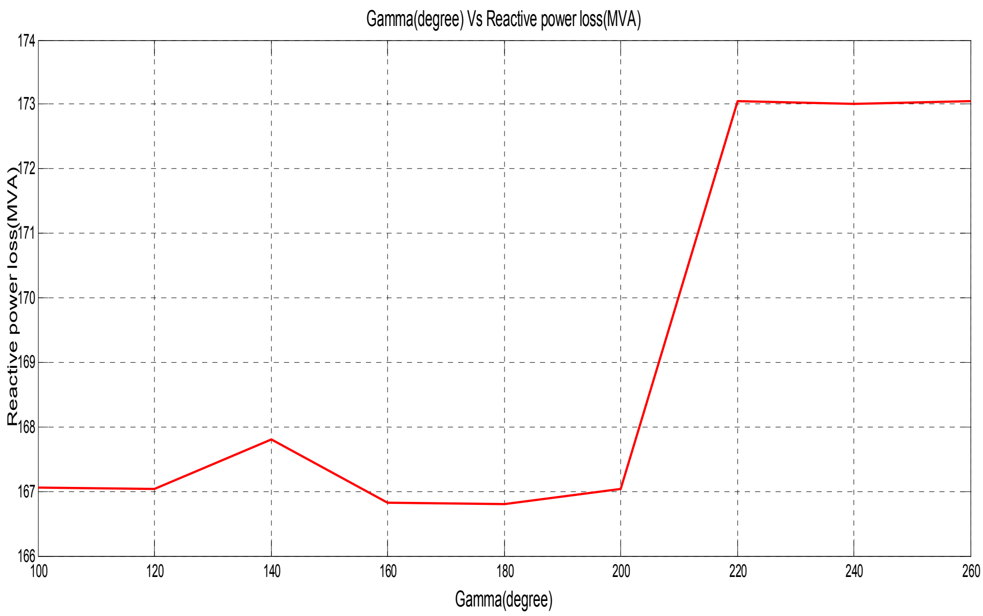


Fig.4.12Variation of reactive power loss for different value or ‘γ’ at ‘r’=0.04

4.3 IEEE 5 Bus system:

To perform the UPEC in terms of power losses analysis 5 bus networks have taken from G.W.Stagg & A.H.El-Abiad, computer methods in power system analysis, 1968 McGraw Hill.

The table 4 represents the variation of active and reactive power losses when UPFC is incorporated in between buses 3-4 at 'r'=0.03.It is shown that when 'γ'=10°, the minimum power losses occurred in the transmission line.

Base MVA=100;
$X_s = 0.025$;
Total active power loss without UPFC=6.483MW;
Total reactive power loss without UPFC= 10.656MVA;

Table4: Active and reactive power losses with respect to gamma

When r=0.03 and UPFC is in between bus 3-4		
$\gamma(degree)$	P_{loss}(MW)	Q_{loss}(MVAR)
140	6.488	10.631
120	6.483	10.508
100	6.470	10.430
80	6.466	10.166
60	6.340	10.105
40	6.330	10.090
20	6.230	9.670
10	6.158	7.897

Here two different graphs are plotted to show the variation of active and reactive power losses with the gamma. The fig 4.15 is for active power loss vs gamma. It is shown from 4.15

and 4.16 that at r=0.03, when the UPFC is in incorporated in bus 3-4 and the value of gamma is decreased the active and reactive power losses are reduced. It is shown from the figure 4.15 and 4.16 that when the value of gamma is 10°, least power loss accrued.

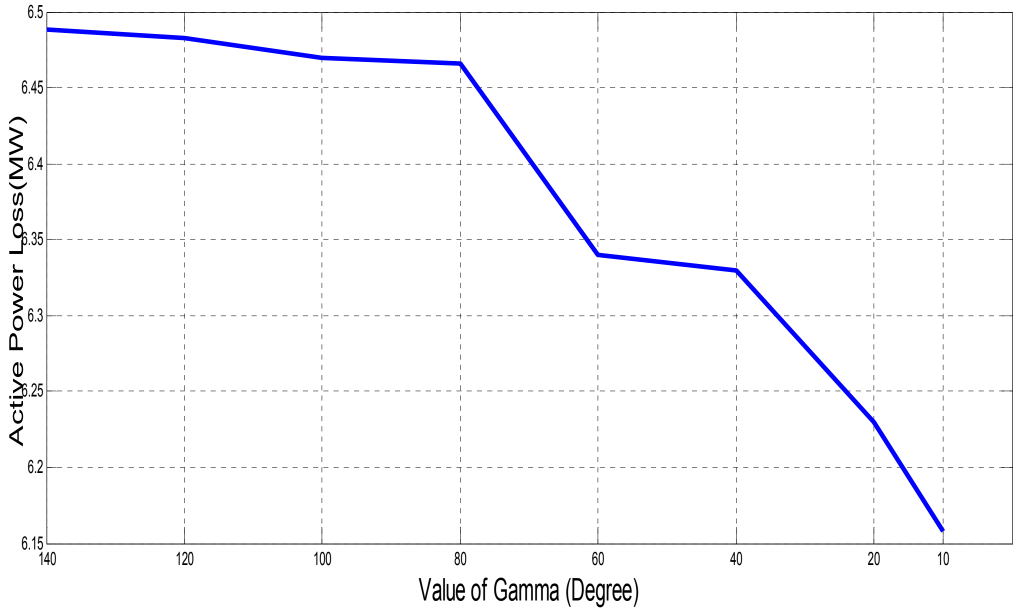


Fig 4.13 Variation of active power loss with 'γ'

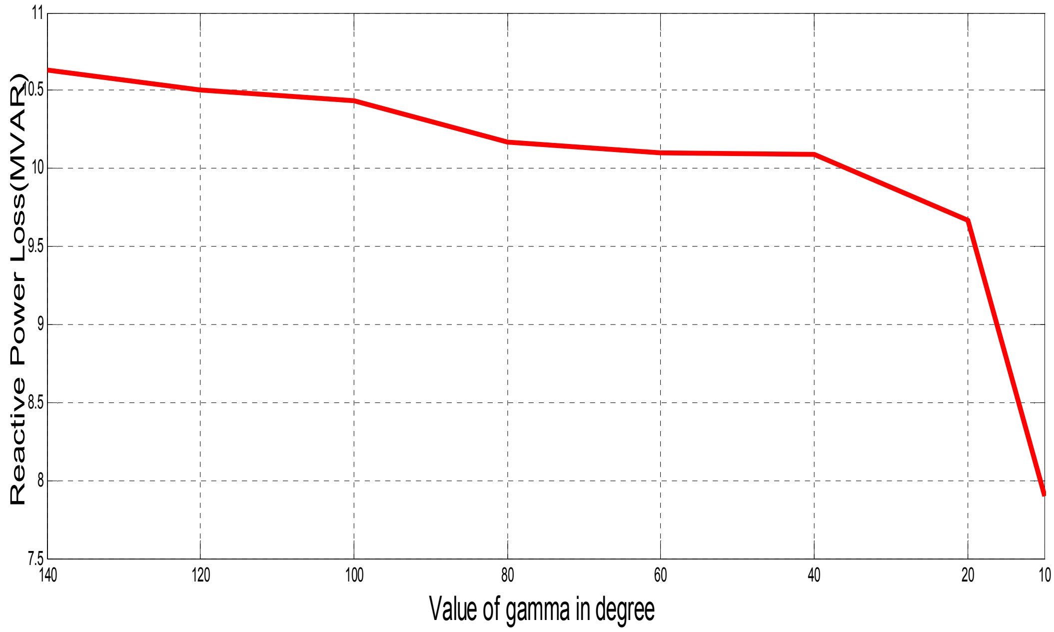


Fig 4.14 Variation of reactive power loss with 'γ'

From fig 4.17, it is observed that when 'γ'=10°, 'r'=0.03 and the UPFC is incorporated in bus 3-4 the bus voltage of all the buses are increased.

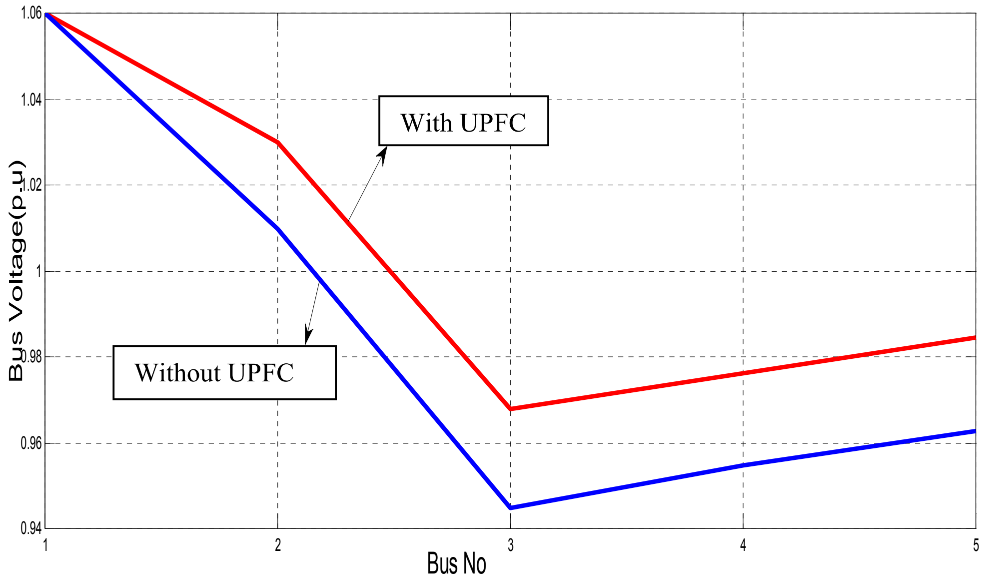


Fig4.15 Bus voltage increased after incorporate UPFC in between buses 3-4

The table 5 is drawn for bus voltage and bus angle without UPFC and for With UPFC. It is shown that the value of bus voltage is increased for all buses when the UPFC is incorporated in bus 3-4 and the angle is reduced.

Table 5: Bus voltage and angle without UPFC and with UPFC

Bus No	Without UPFC		With UPFC in 3-4; r=0.03and 'γ'=10°	
	Voltage (p.u)	Angel(degree)	Voltage(p.u)	Angel(degree)
1	1.0600	0.0000	1.060	0.000
2	1.0100	-10.387	1.03	-10.279
3	0.945	-18.402	0.968	-17.873
4	0.955	-19.615	0.9762	-19.073
5	0.963	-17.152	0.9846	-16.753

Chapter 5

CONCLUSION & FUTURE SCOPE

5.1 Conclusion:

In this study, A MATLAB program has executed to incorporate the steady-state mathematical model of UPFC in the conventional NR power flow algorithm. The steady state effect of UPFC has shown in different system. It is shown that when UPFC is incorporated in between two buses in the system, for different value of ‘r’ and $'\gamma'$ the active and reactive power loses are reduced. It is also shown that not only the power losses are reduced, the voltage profile of the every buses also improved after incorporate UPFC.

5.2 Future Scope:

Various optimization methods can be used to get the optimal location of the UPFC in the system. In this project the switching losses of the two converters is not considered. This research can be done with considering the losses of UPFC. The research can be extended for applying the similar techniques to the transmission line having other FACTS devices which are not included in the proposed study.

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Publication

1. Mithu Sarkar,“Effect of UPFC Allocation on Transmission System Power Loss”, Int. Conf. on Energy Efficient Technologies for System Sustainability (ICEETS-2013), IEEE, Tamilnadu, 10th – 12th April 2013.